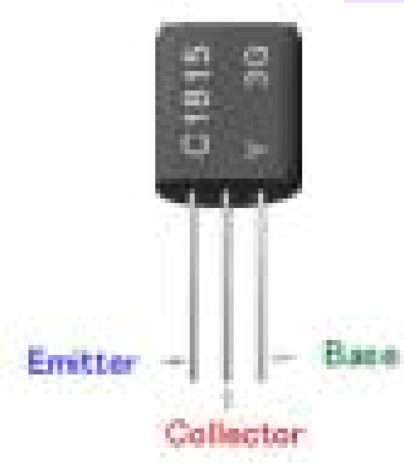
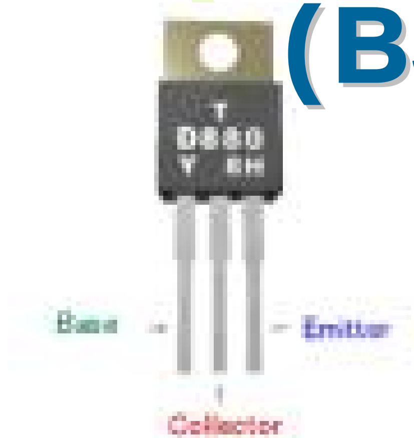
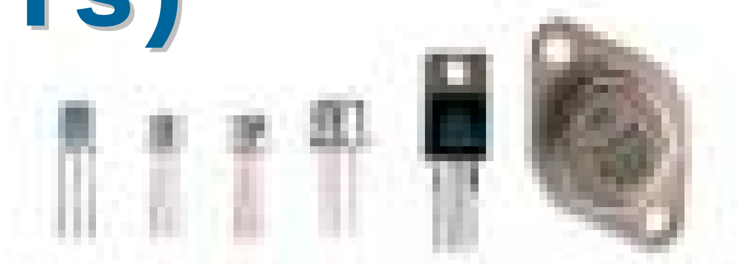
Lecture 04

Bipolar junction transistors (BJTs)







Topics

- Transistor physic operation
- Transistor operation modes
- Transistor current-voltage characteristics

Transistor=Transfer resistor

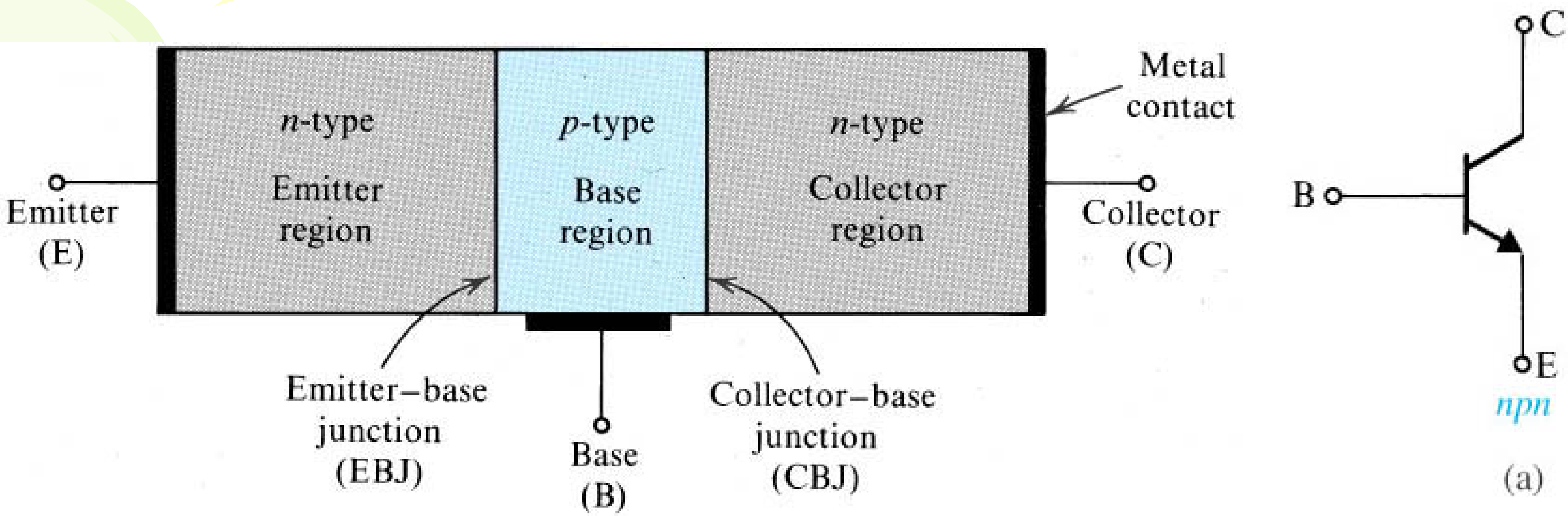
Two categories of transistor

1. **BJT**
2. **FET**
   - **MOSFET**
   - **JFET**

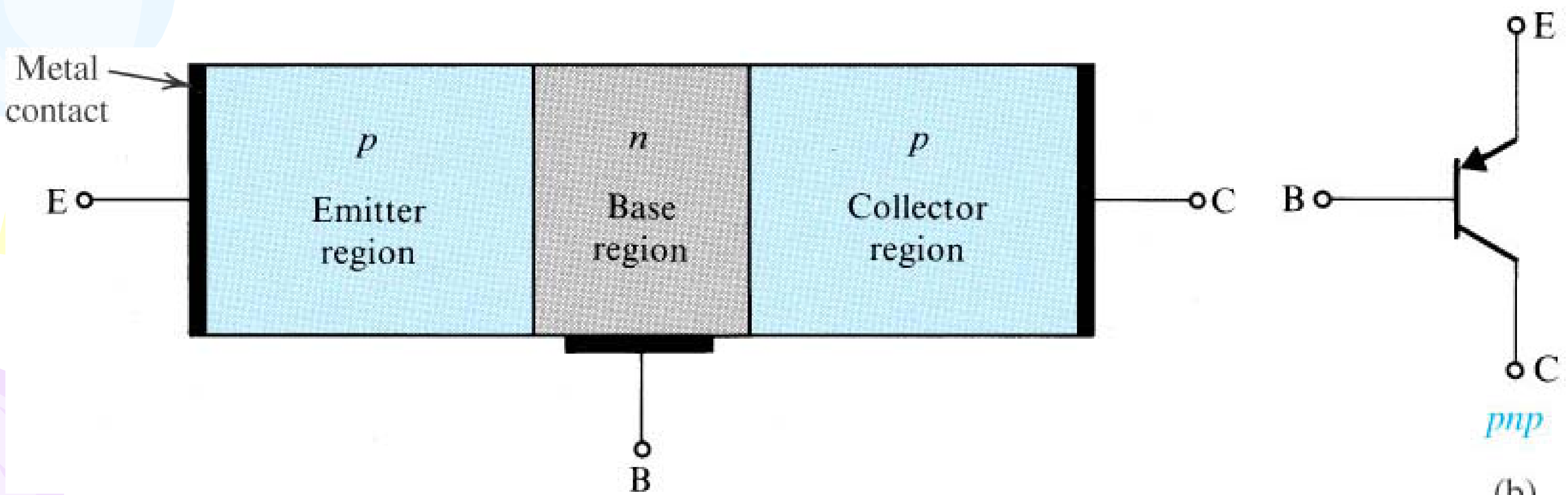
L'effet transistor a été découvert en 1947 par les américains John Bardeen, William Shockley et Walter Brattain, chercheurs de la compagnie Bell Téléphone. Ils ont reçu le prix Nobel de physique en 1956.

Quelques jalons (Intel)

- **1971 : 4004 : 2 300 transistors**
- **1978 : 8086 : 29 000 transistors**
- **1982 : 80286 275 000 transistors**
- **1989 : 80486 : 1,16 millions de transistors**
- **1993 : Pentium : 3,1 millions de transistors**
- **1995 : Pentium Pro : 5,5 millions de transistors**
- **1997 : Pentium II : 27 Millions de transistors**
- **2001 : Pentium 4 : 42 millions de transistors**
- **2004 : Pentium 4 EE : 169 millions de transistors**

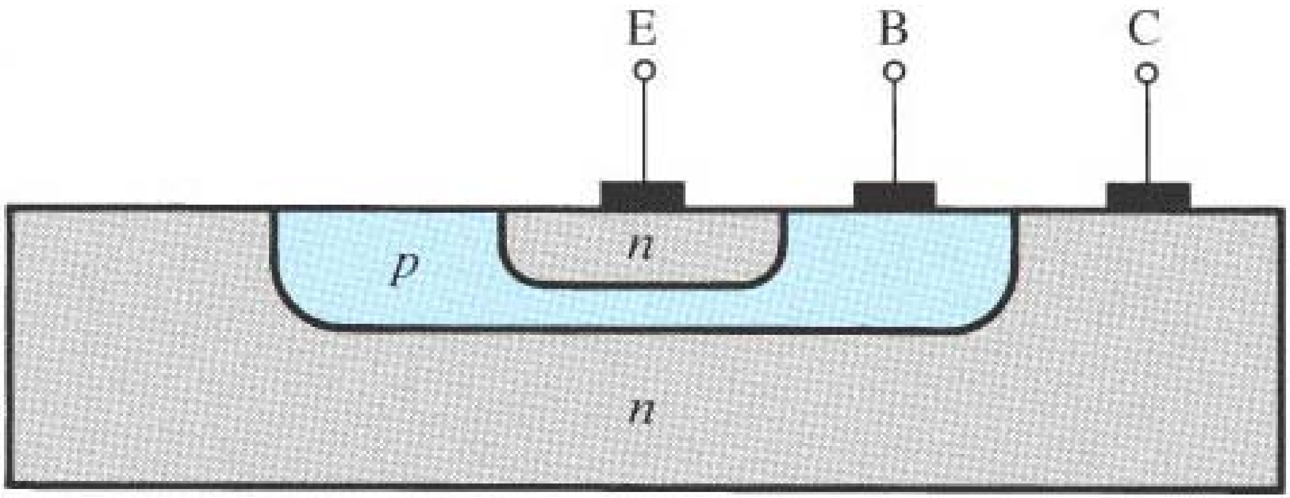

n-type
Emitter region
p-type
Base region
n-type
Collector region
Metal contact
Emitter (E)
Collector (C)
Emitter–base junction (EBJ)
Base (B)
Collector–base junction (CBJ)
C
B
E
npn

(a)


Metal contact
p
Emitter region
n
Base region
p
Collector region
E
C
B
E
B
C
pnp

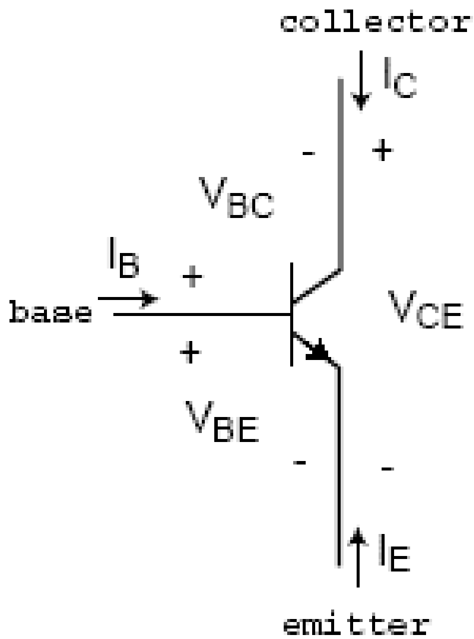
(b)

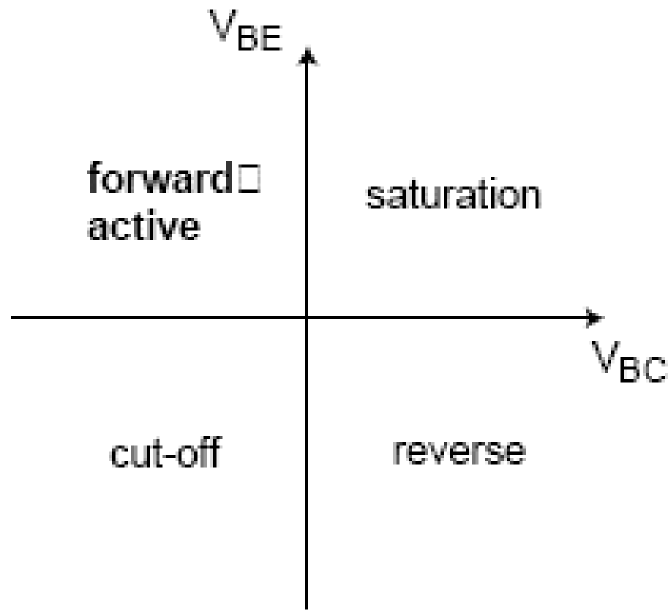
Structure of transistor



射極：代號E，寬度居三者之中，參雜濃度最濃。
基極：代號B，寬度最薄，參雜濃度最低。
集極：代號C，寬度最大，參雜濃度適中。

BJT operation mode		
mode	EB junction	CB junction
active	forward	reverse
Reverse active	reverse	forward
saturation	forward	forward
cutoff	reverse	reverse

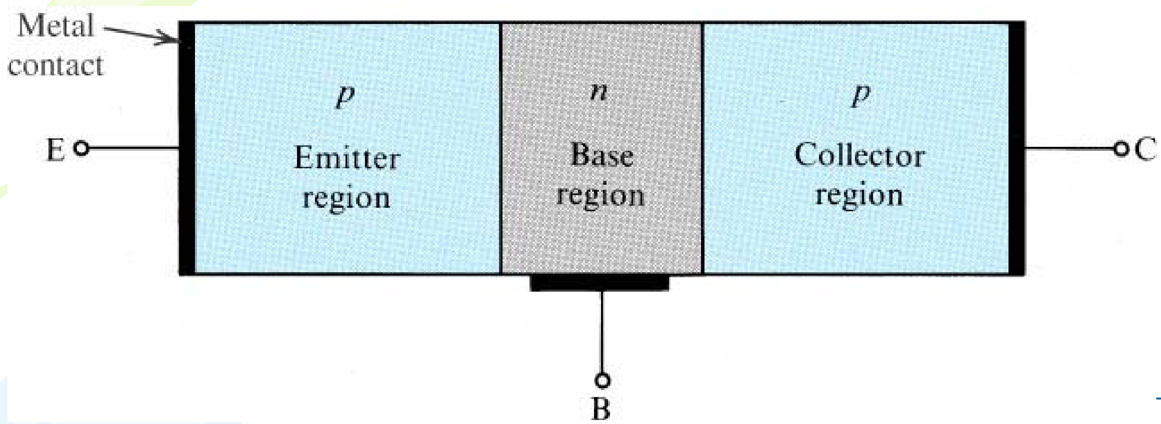


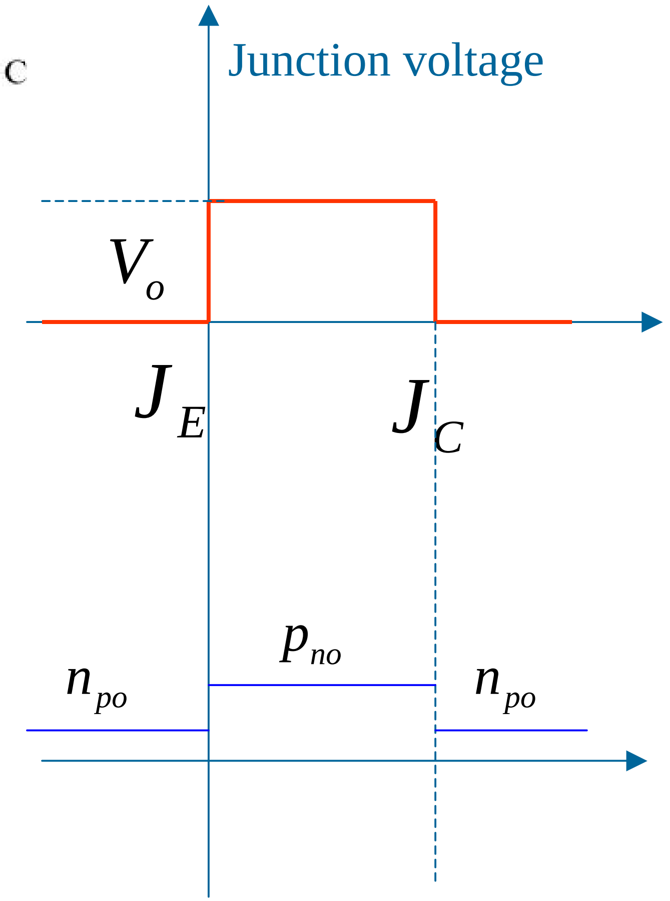


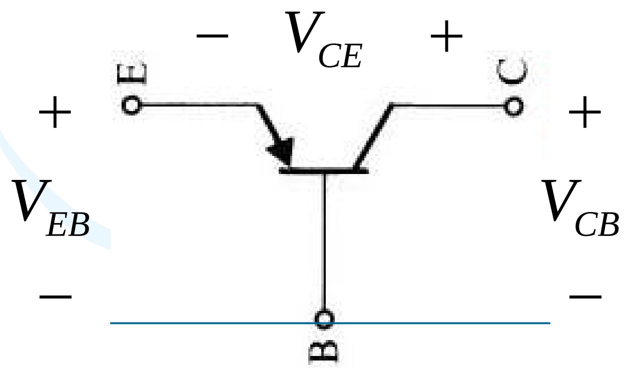
comparison

- NPN (electrons) fast than PNP (holes)
- NPN easy to product

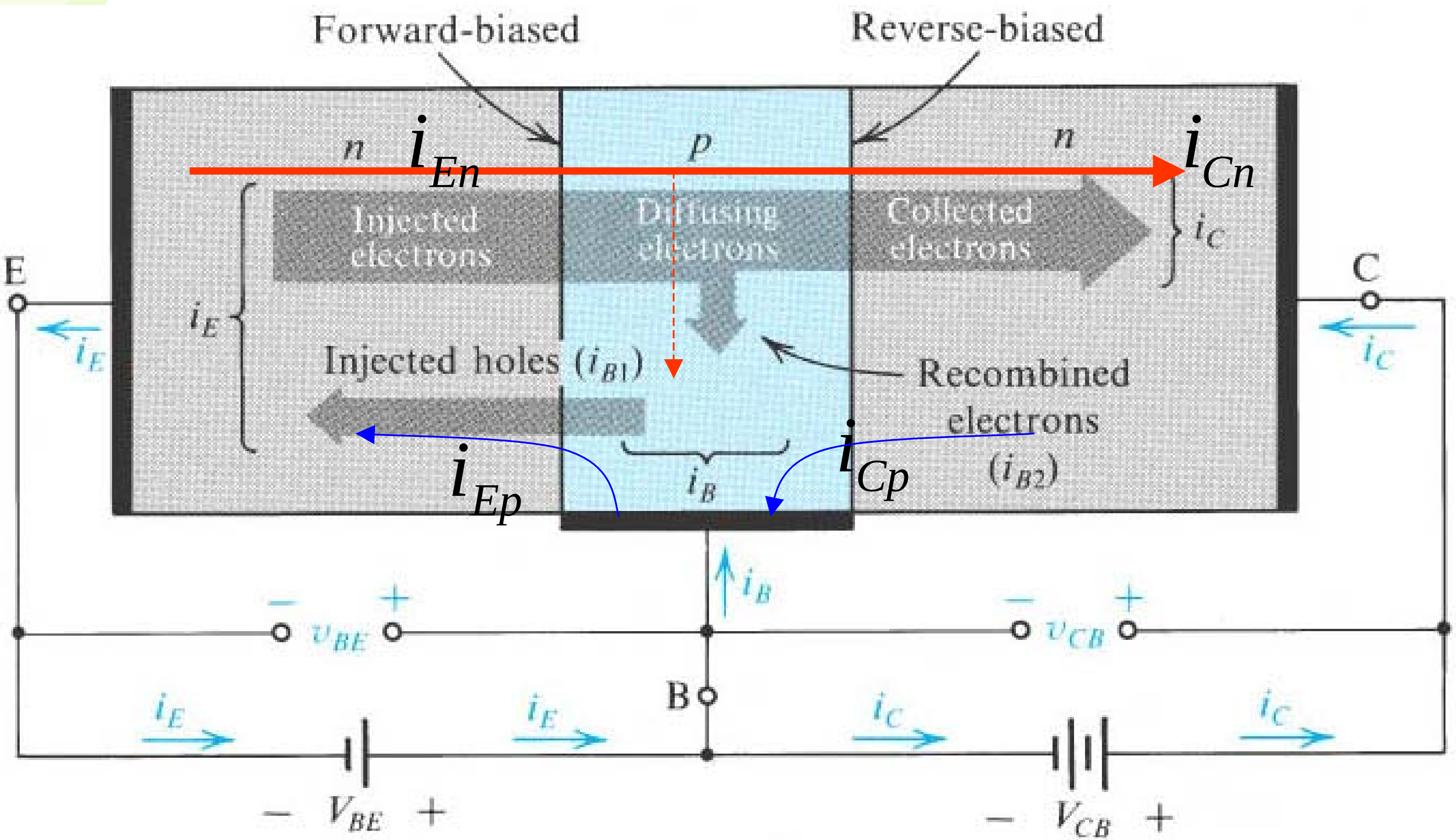
PNP transistor in open circuit

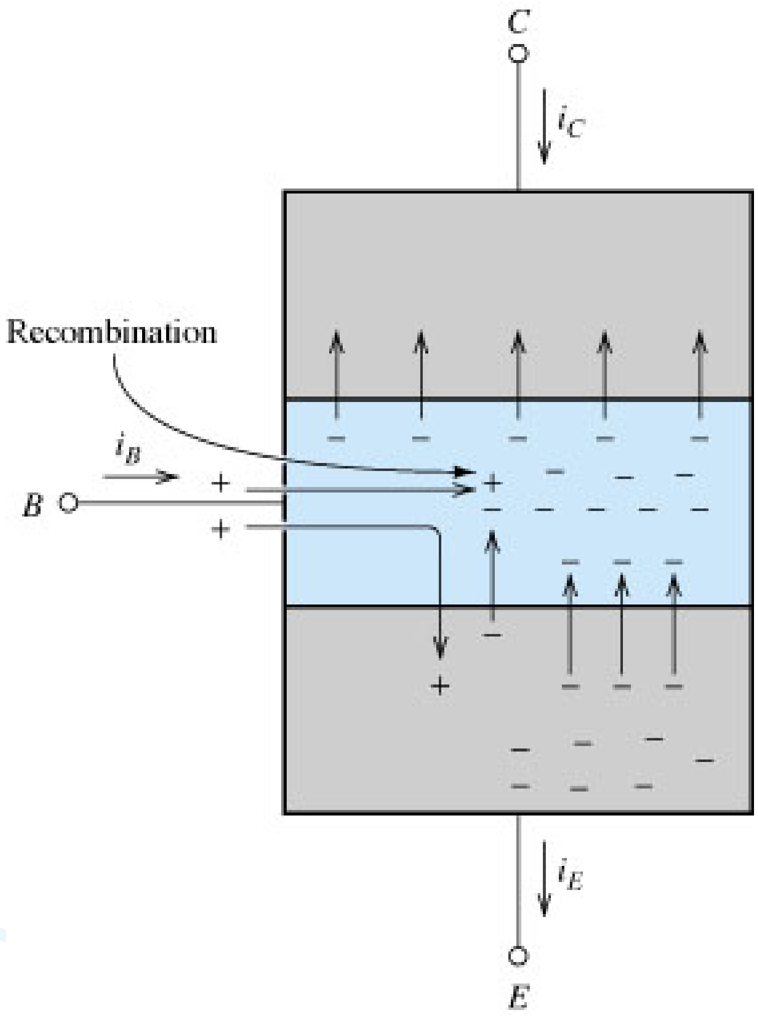






NPN transistor (Active mode)




C
i_C
Recombination
i_B
B
E
i_E

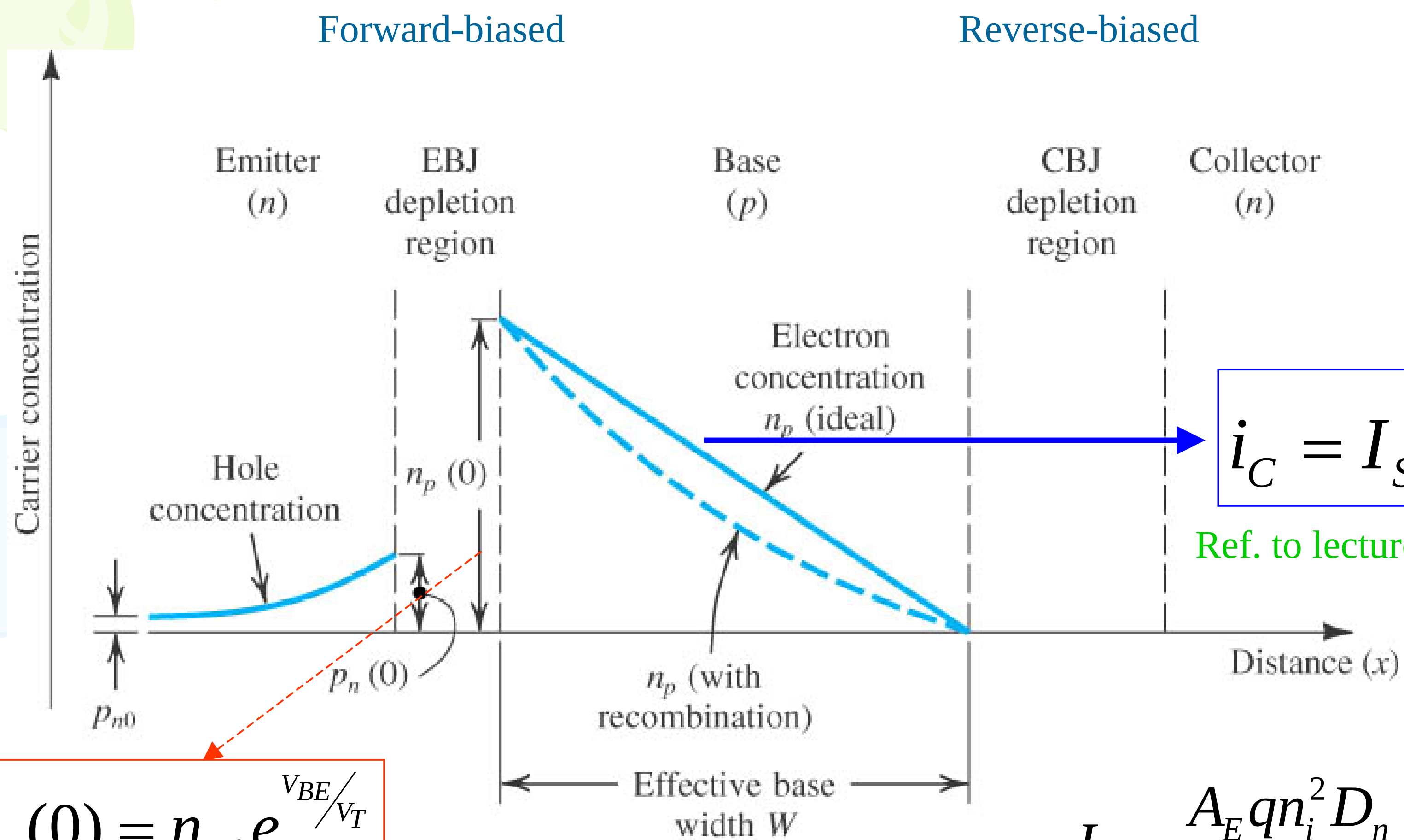
1. J_E forward-Biased : electrons injected from emitter into base (i_{En}),
   holes injected from base into emitter (i_{Ep}).
2. In base: some electrons combined with holes (i_{B2}),
   most of electrons diffused to collector (i_{Cn}).
3. J_C reverse-Biased : electrons swept across the depletion region (i_{Cn}),
   small saturation current in depletion region (i_{Cp}),

$$\boxed{\begin{aligned} i_E &= i_{En} + i_{Ep} \\ i_C &= i_{Cn} + i_{Cp} \\ i_B &= i_{Ep} + i_{B2} - i_{Cp} \\ i_{B2} &= i_{En} - i_{Cn} \end{aligned}}$$

$$\boxed{\begin{aligned} i_{En} &>> i_{Ep} \\ i_{Cn} &>> i_{Cp} \end{aligned}}$$

$$\boxed{i_E = i_C + i_B}$$

Minority-carrier concentrations



$$i_C = I_S e^{V_{BE}/V_T}$$

Ref. to lecture 02 page24

$$n_p(0) = n_{p0} e^{V_{BE}/V_T}$$

$$I_s = \frac{A_E q n_i^2 D_n}{W N_A}$$

Ref. to lecture 02 page22

Active mode

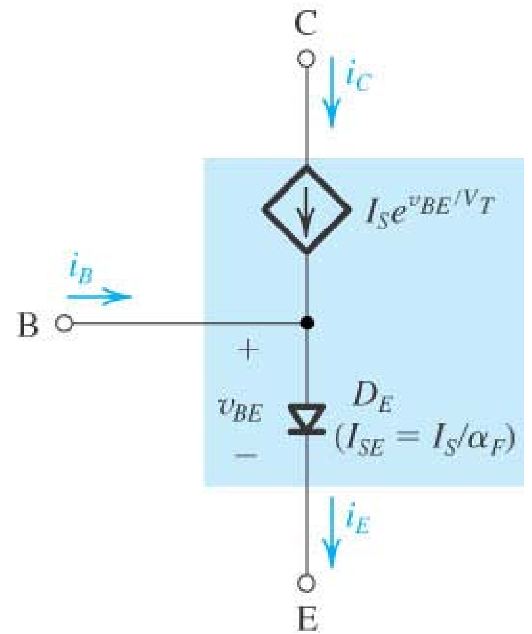
$$i_C = I_S e^{V_{BE}/V_T}$$

$$\boxed{i_B = \frac{i_C}{\beta}}$$

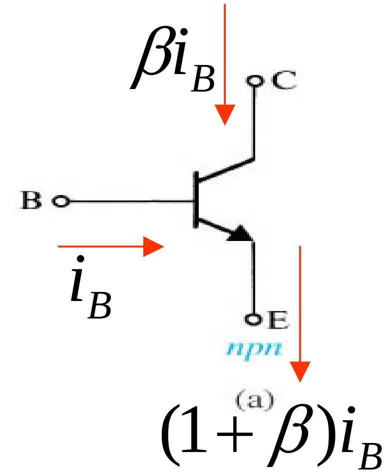
$$\Rightarrow i_B = \frac{I_S}{\beta} e^{V_{BE}/V_T}$$

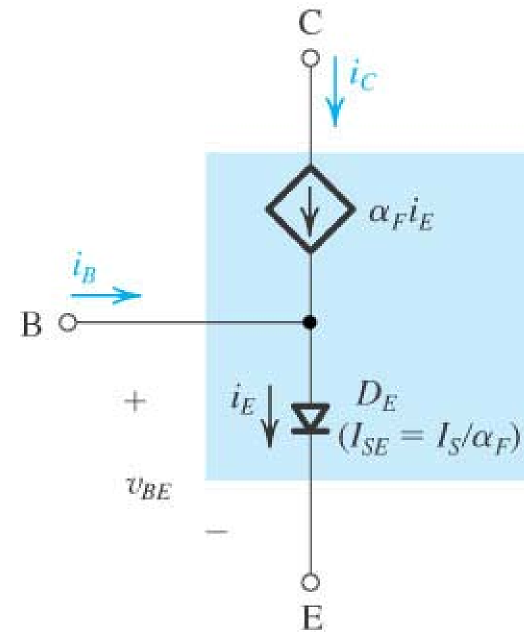
$$i_E = i_C + i_B$$

$$\Rightarrow \boxed{i_E = \frac{1+\beta}{\beta} i_C = \frac{1}{\alpha} i_C}$$



(a)

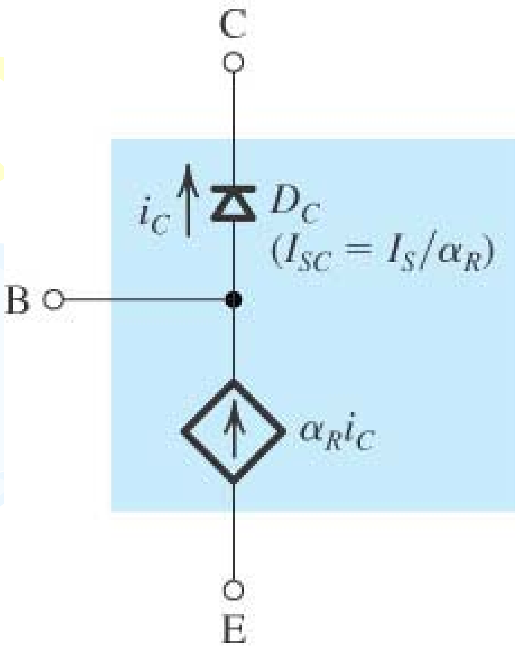


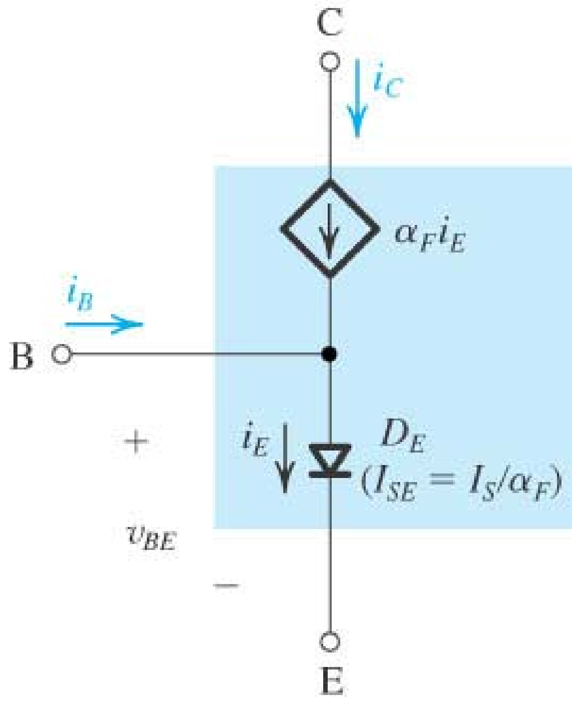


(b)

NPN transistor (reverse active mode)

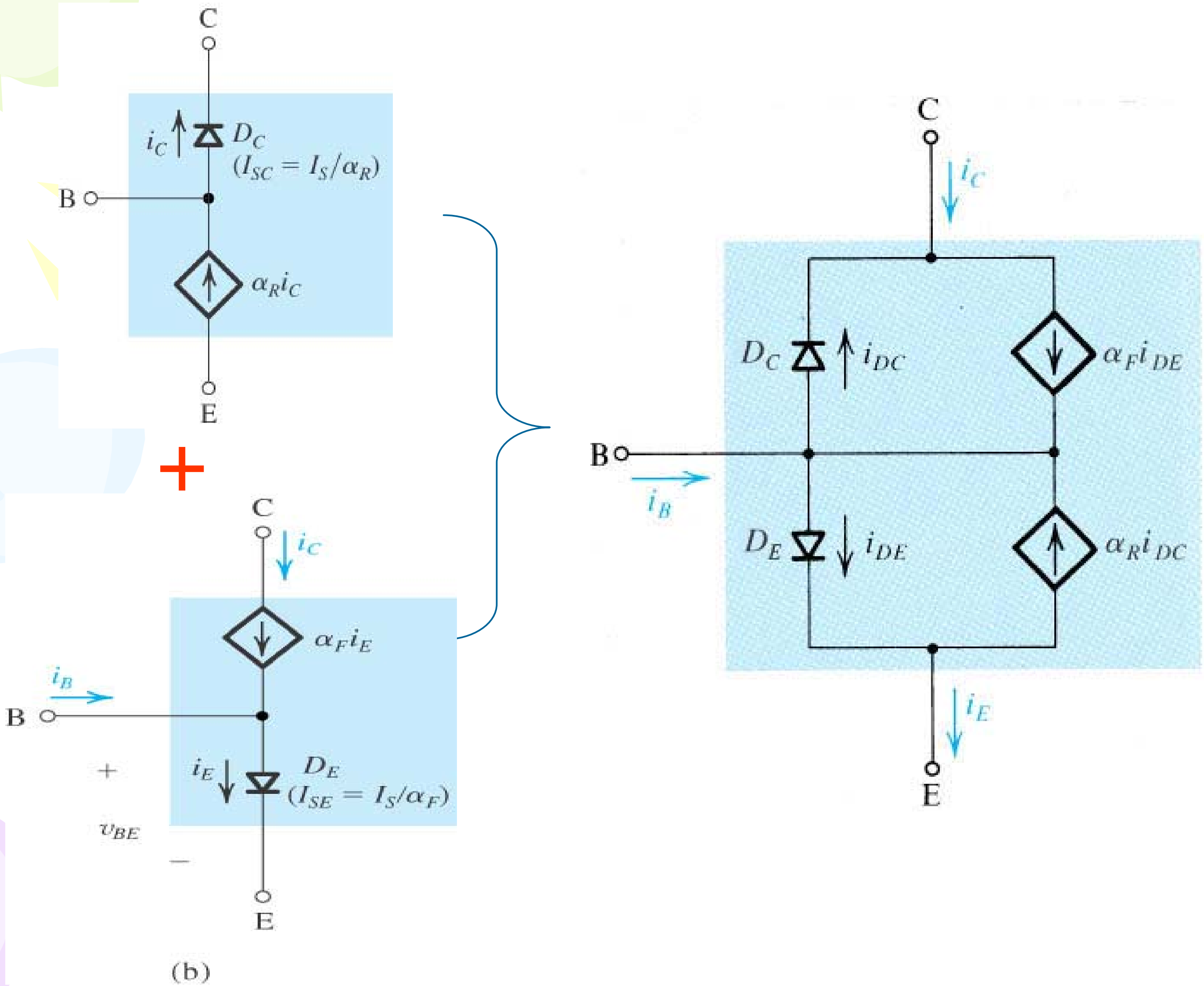
J_E reverse and J_C forward





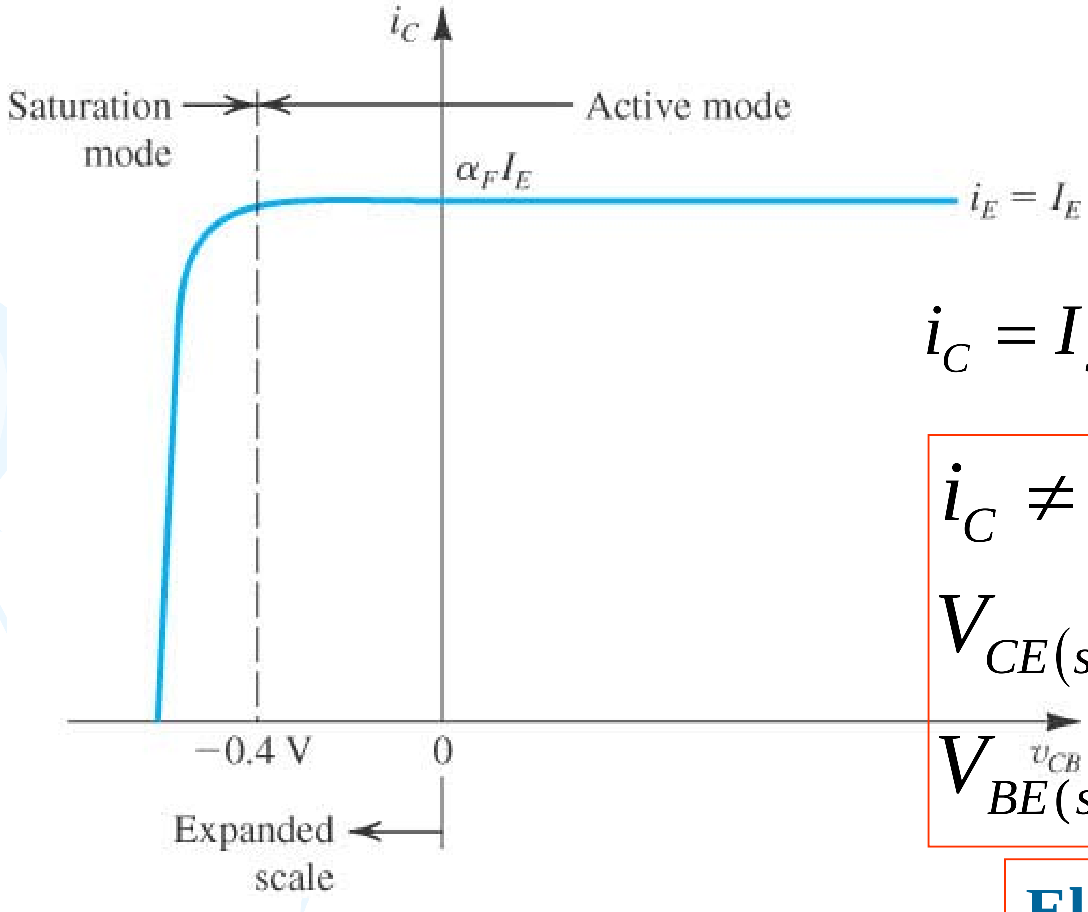
(Active mode)

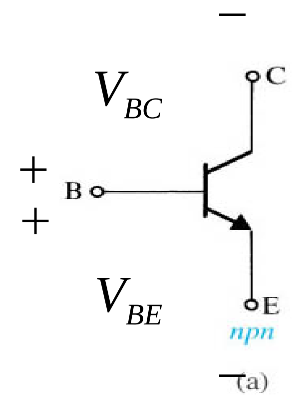
NPN transistor (Ebers_Moll mode) (for four modes)



NPN transistor (saturation mode)

J_E Forward and J_C Forward



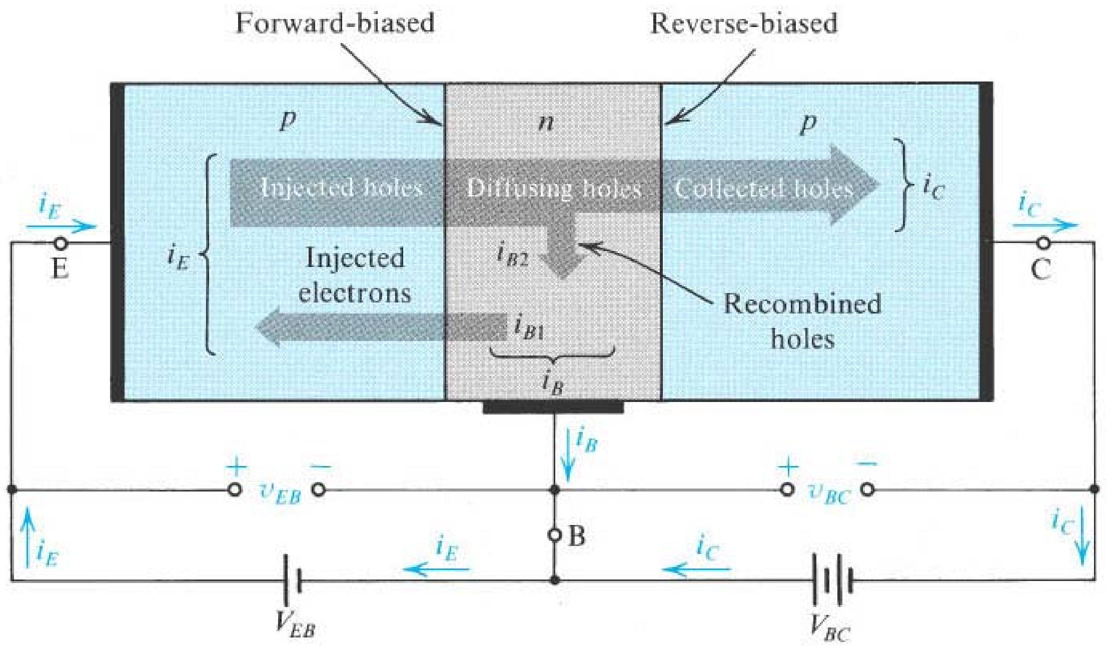


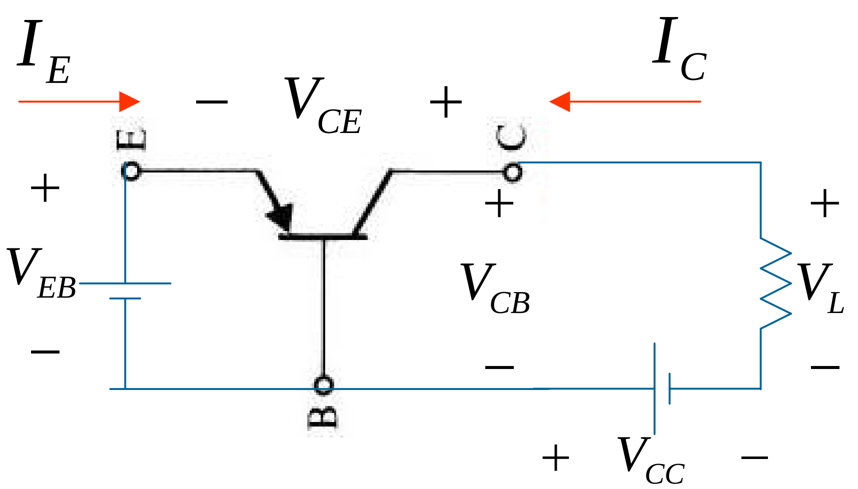
$$i_C = I_S e^{V_{BE}/V_T} - \frac{I_S}{\alpha_R} e^{V_{BC}/V_T}$$

$$\boxed{\begin{aligned} & i_C \neq \beta i_B \\ & V_{CE(sat)} = 0.2V\,(Si) \\ & V_{BE(sat)} = 0.8V\,(Si) \end{aligned}}$$

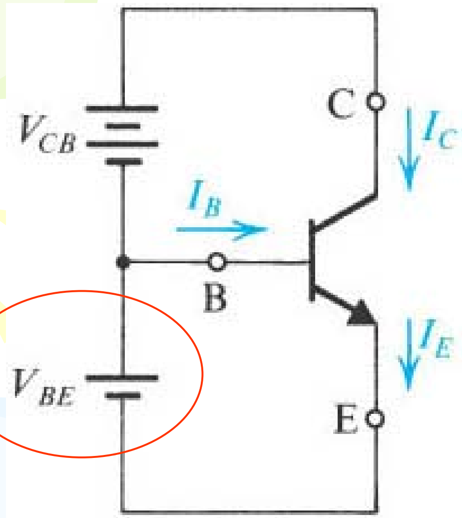
Electronic Switch

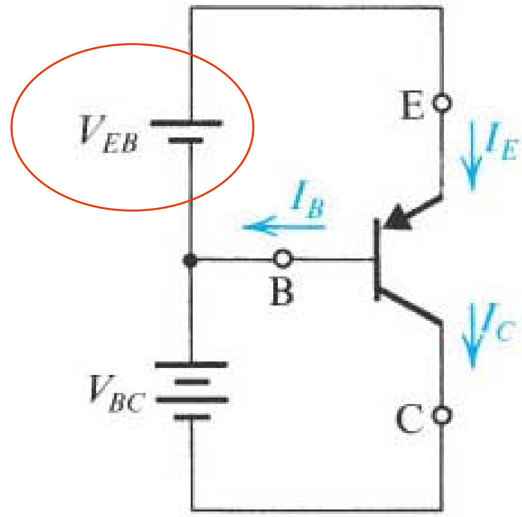
pnp transistor
Exercise





Characteristic in Active mode (for Amplifier)





$$i_C = I_S e^{V_{BE}/V_T}$$

$$i_C = \beta i_B$$

$$i_E = \frac{1}{\alpha} i_C$$

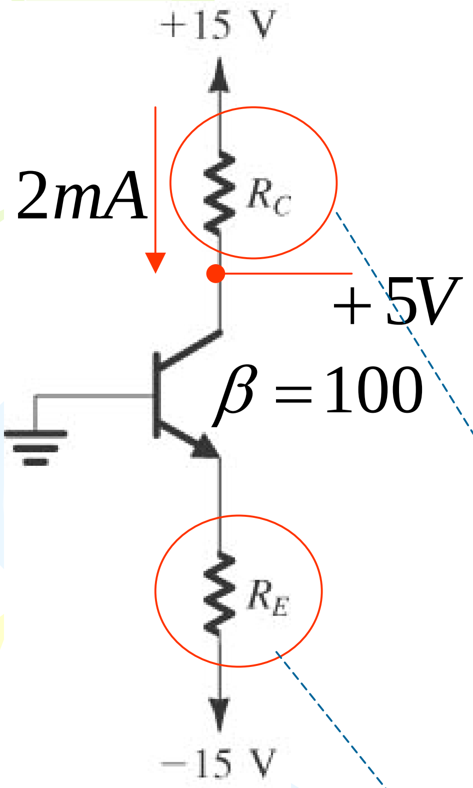
$$\boxed{\begin{array}{l} \beta >> 1 \\ \alpha \approx 1 \end{array}}$$

$$i_C = I_S e^{V_{EB}/V_T}$$

$$i_C = \beta i_B$$

$$i_E = \frac{1}{\alpha} i_C$$

Example 5.1



(a)

Consider J_{BE}:

$$V_2 - V_1 = V_T \ln \frac{I_2}{I_1}$$

Ref. to lecture 02 page24

$$V_{BE} - 0.7 = V_T \ln \frac{2mA}{1mA}$$

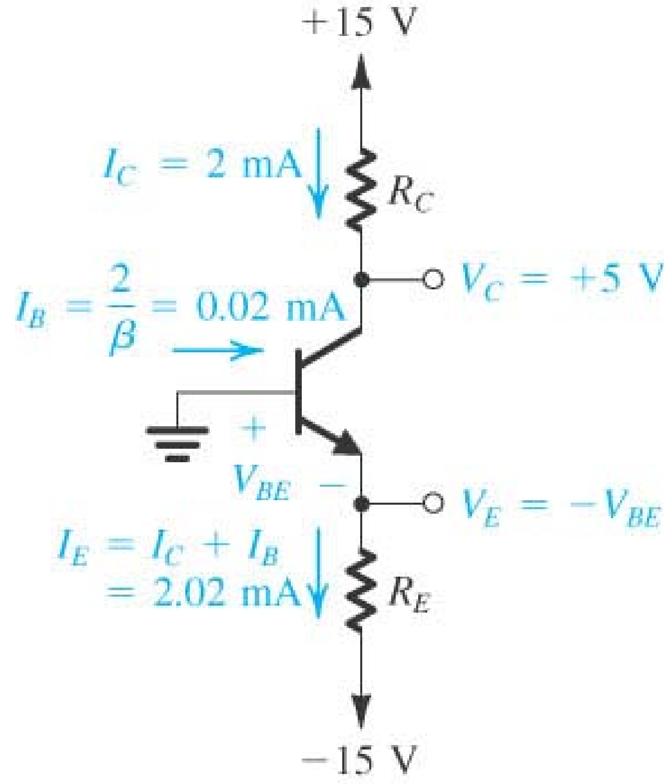
$$\Rightarrow V_{BE} = 0.717V$$

$$R_C = \frac{10V}{2mA} = 5k\Omega$$

$$I_E = I_C + I_B = 2mA + \frac{2mA}{100} = 2.02$$

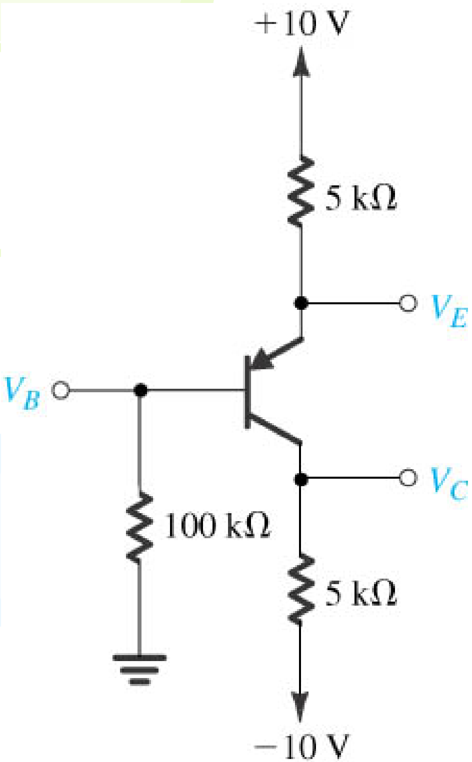
$$V_E = -V_{BE} = -0.717$$

$$R_E = \frac{-0.717-(-15)}{2.02} = 7.07k\Omega$$



(b)

Exercise 5.11



$$given \quad V_B = +1V, \quad V_E = +1.7V$$

$$find \quad \alpha, \beta, and \quad V_C$$

$$I_E = \frac{10-1.7}{5k} = 1.66mA$$

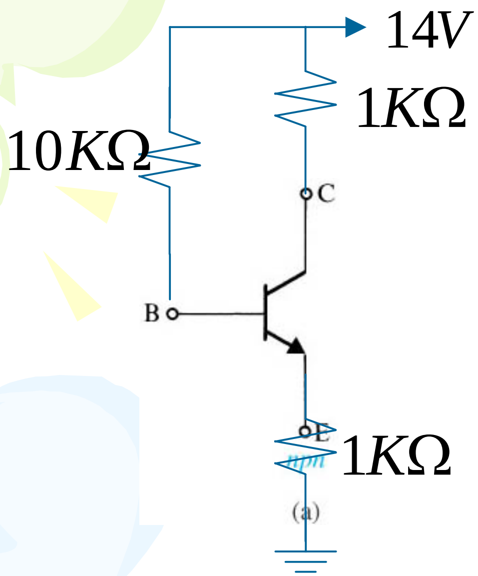
$$I_B = \frac{1}{100k} = 0.01mA$$

$$I_C = I_E - I_B = 1.65mA$$

$$\beta = \frac{I_C}{I_B} = \frac{1.65}{0.01} = 165$$

$$\alpha = \frac{\beta}{\beta+1} = 0.994$$

Example : *the transistor is work in saturation mode find the minimum* β



$$V_{BE(sat)} = 0.8V$$

$$V_{CE(sat)} = 0.2V$$

$$I_{C(sat)} \times 1K + 0.2 + (I_{C(sat)} + I_{B(sat)}) \times 1K = 14V$$

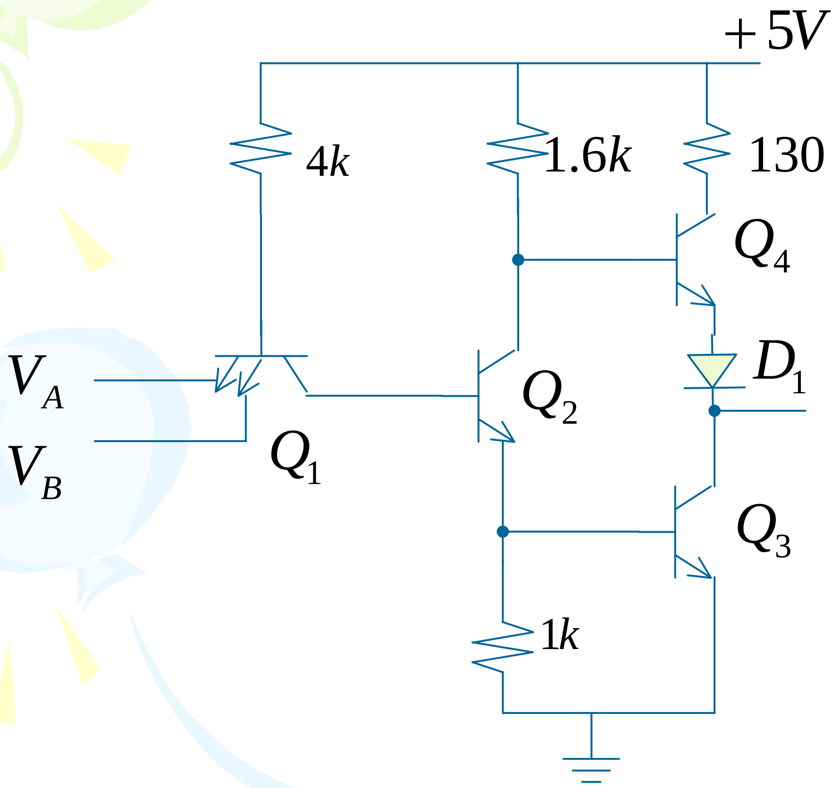
$$I_{B(sat)} \times 10K + 0.8 + (I_{C(sat)} + I_{B(sat)}) \times 1K = 14V$$

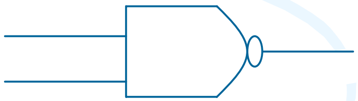
$$I_{C(sat)} = 6.6mA$$

$$I_{B(sat)} = 0.6mA$$

$$\beta_{\min} = \frac{6.6}{0.6} = 11$$

Example (TTL circuit)





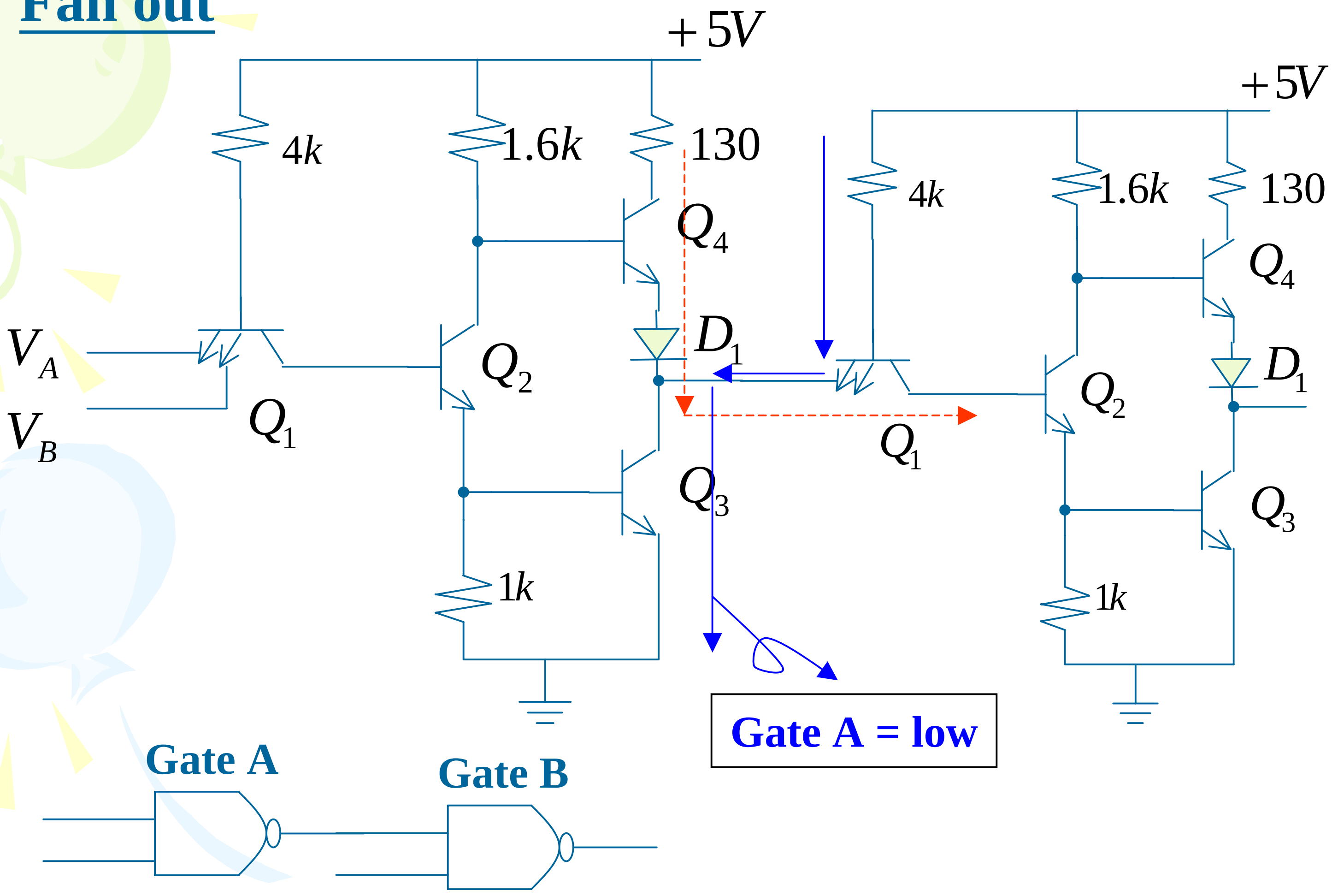
V_A and A_B =+ 5V

Q1 : reverse active
Q2 and Q3 : saturation
Q4 and D1 : cut-off

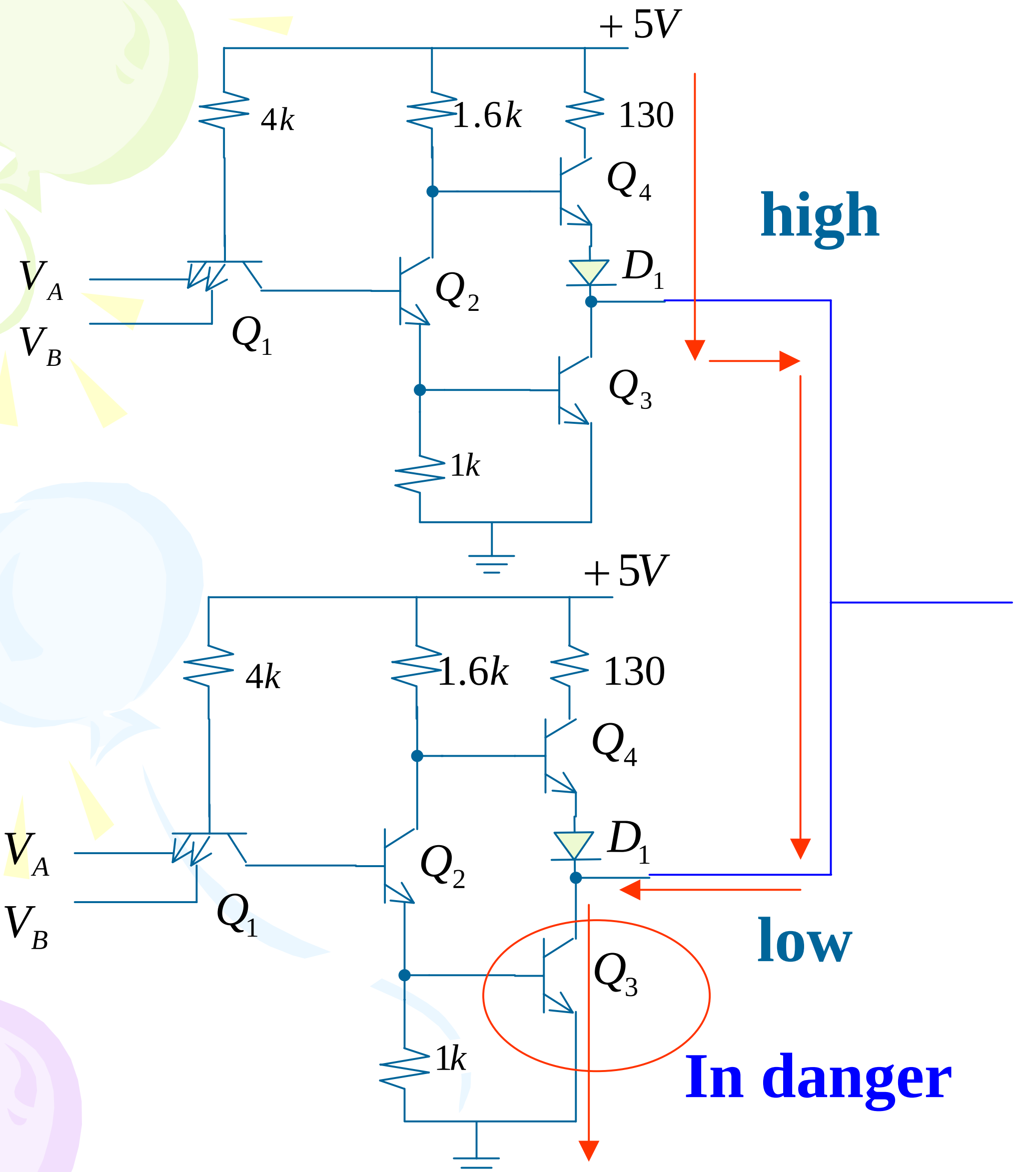
V_A or A_B = +0.1~0.2V

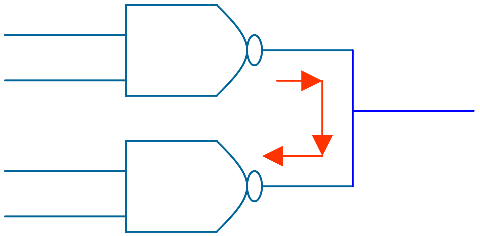
Q1 : saturation
Q2 and Q3 : cut off
Q4 : saturation
D1 : on

Fan out

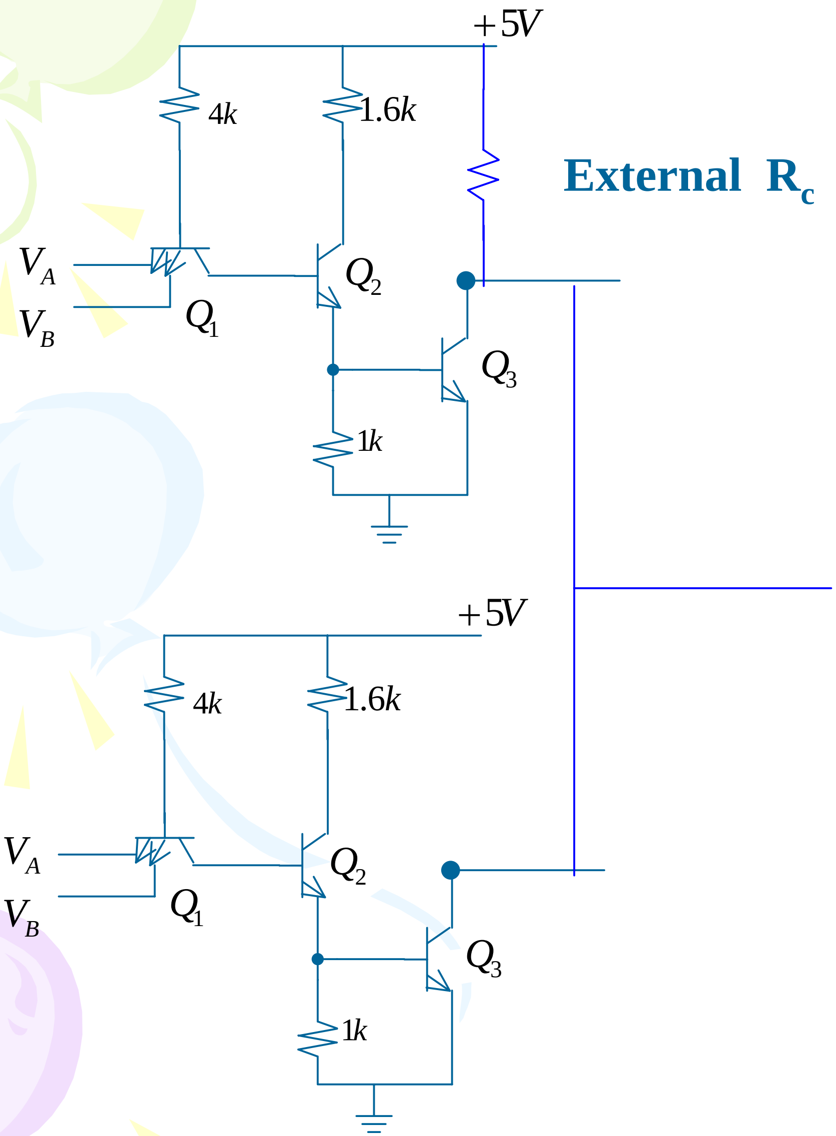


+5V
4k
1.6k
130
Q4
Q2
D1
Q1
Q3
1k
VA
VB
+5V
4k
1.6k
130
Q4
D1
Q2
Q1
Q3
1k
Gate A = low
Gate A
Gate B


+5V
4k
1.6k
130
Q4
D1
Q2
Q1
Q3
1k
VA
VB
high
+5V
4k
1.6k
130
Q4
D1
Q2
Q1
Q3
1k
VA
VB
low
In danger



Open collector



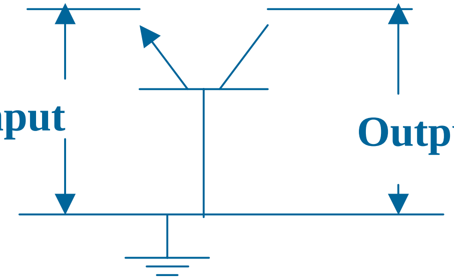
Current-voltage characteristics

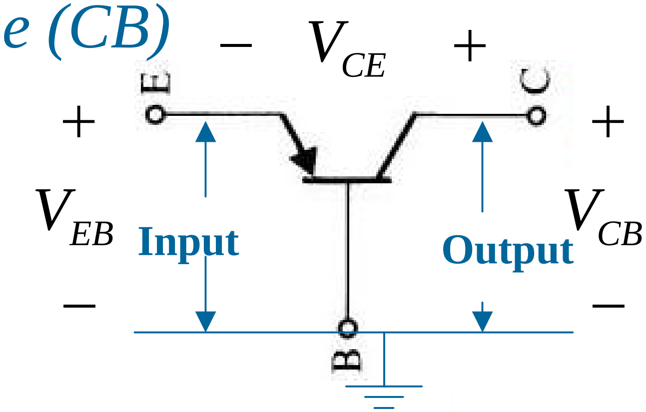
- i_C -- V_{BE}
- i_C -- V_{CB}
- i_C -- V_{CE}

BJT configurations

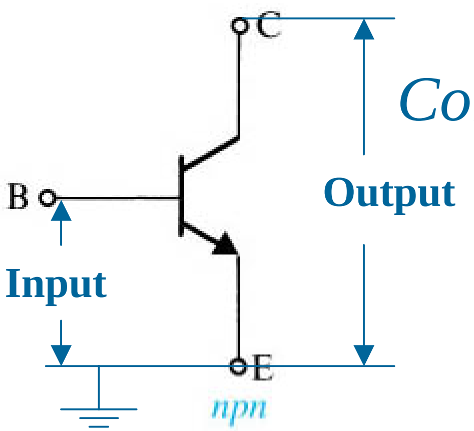
- *Common-Base (CB)*
- *Common-Emitter (CE)*
- *Common-Collector (CC)*

Common-Base (CB)

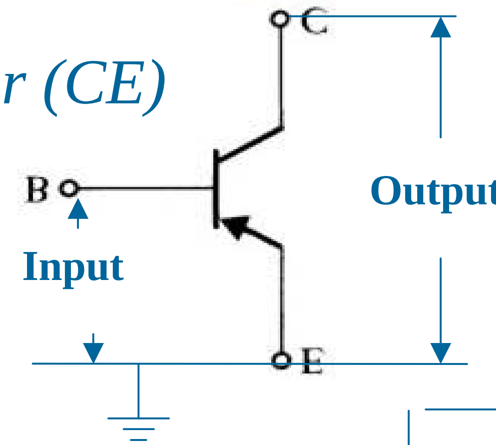




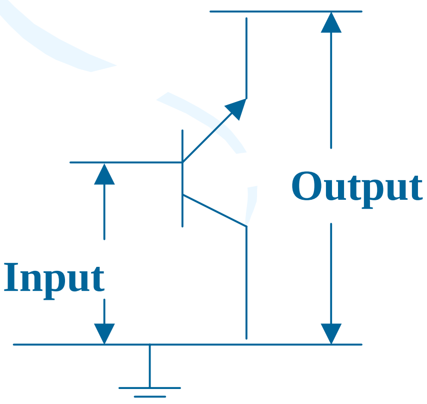
Common-Emitter (CE)

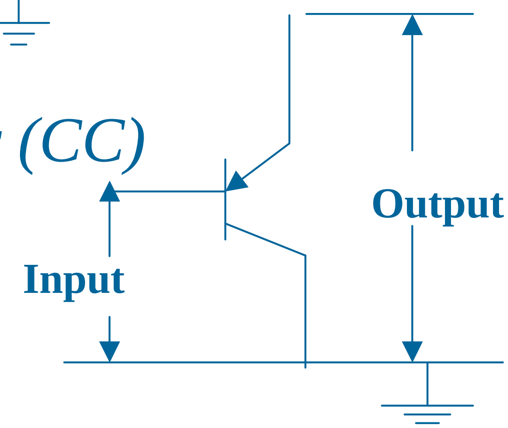


(a)



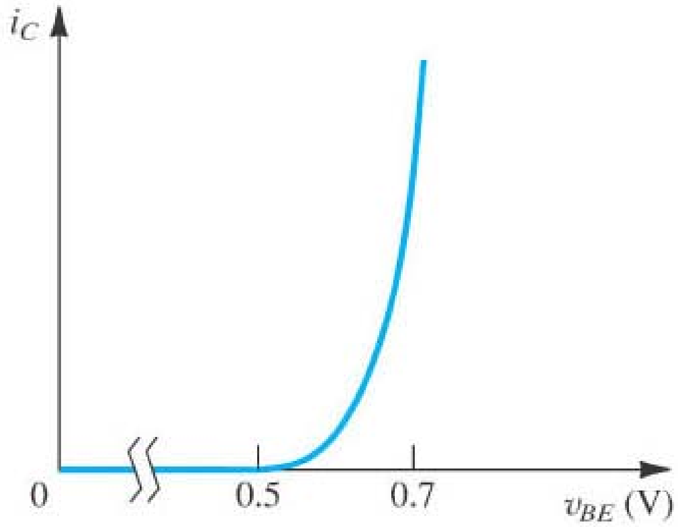
Common-Collector (CC)

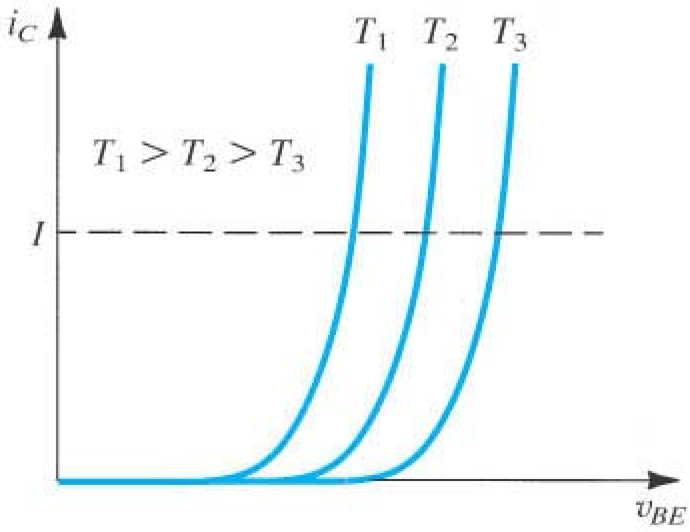




Transistor i_C -- V_{BE} Characteristic (change T)

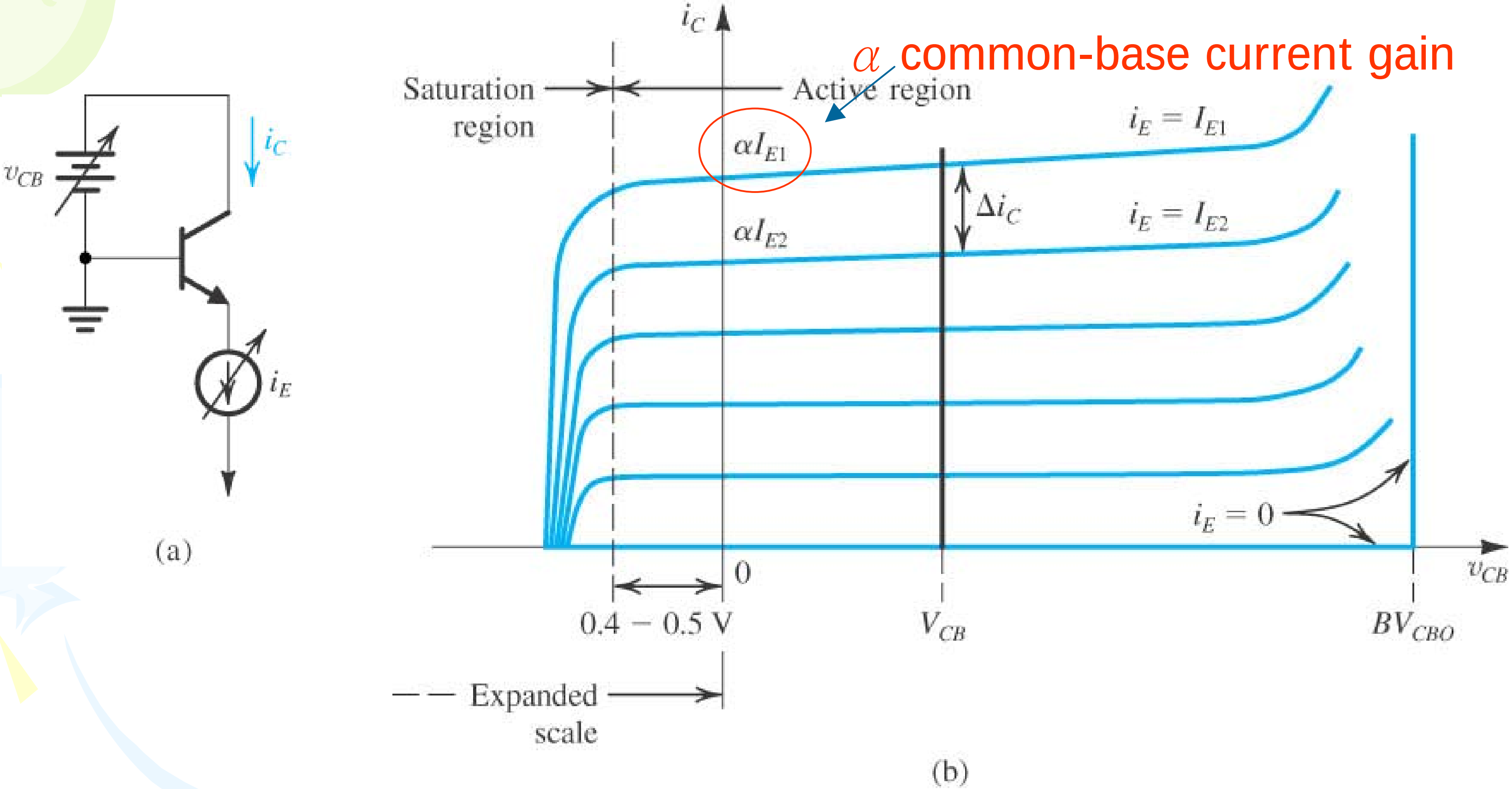
$$\boxed{i_C = I_S e^{V_{BE}/V_T}}$$



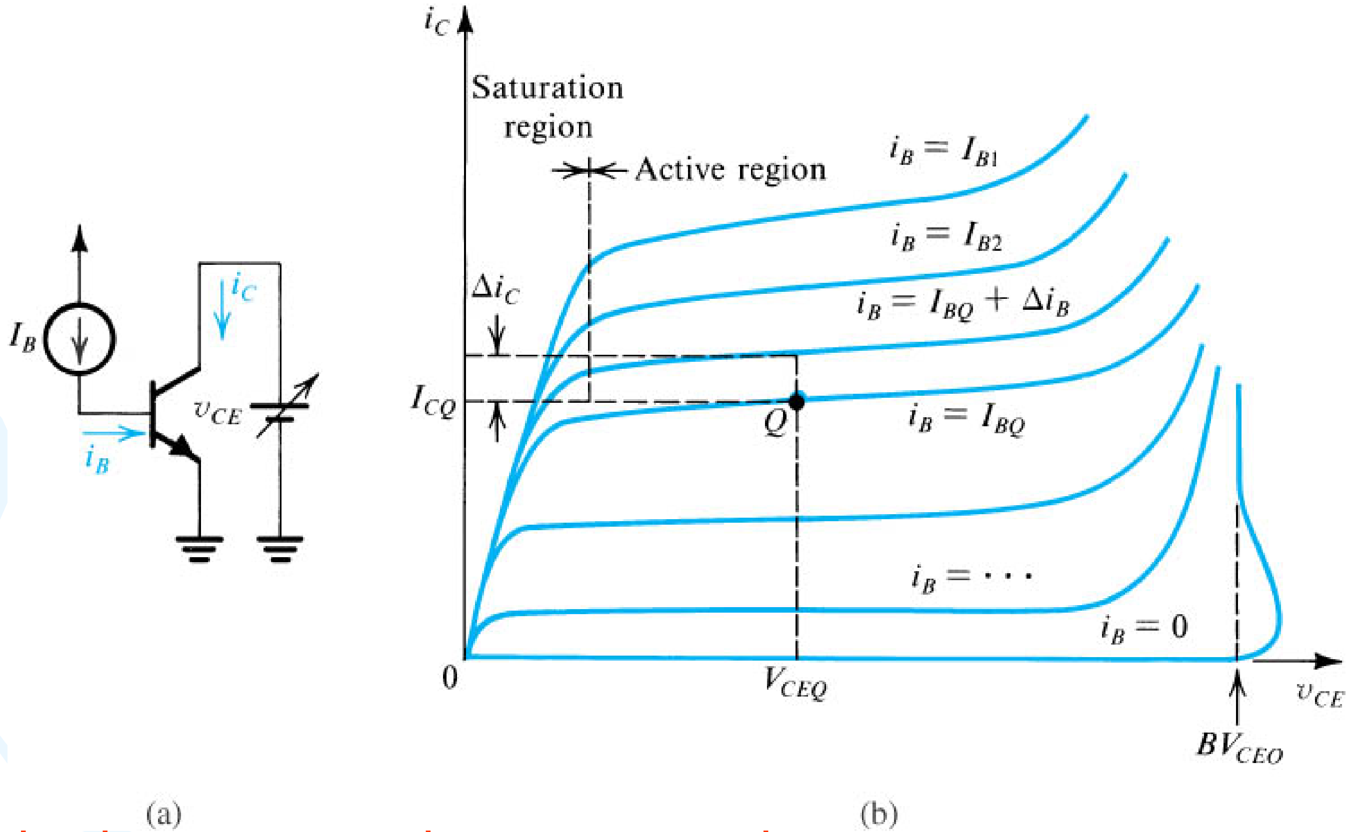


Transistor i_C -- V_{CB} Characteristic (change i_E)

α common-base current gain



Transistor i_C -- V_{CE} Characteristic (change I_B)

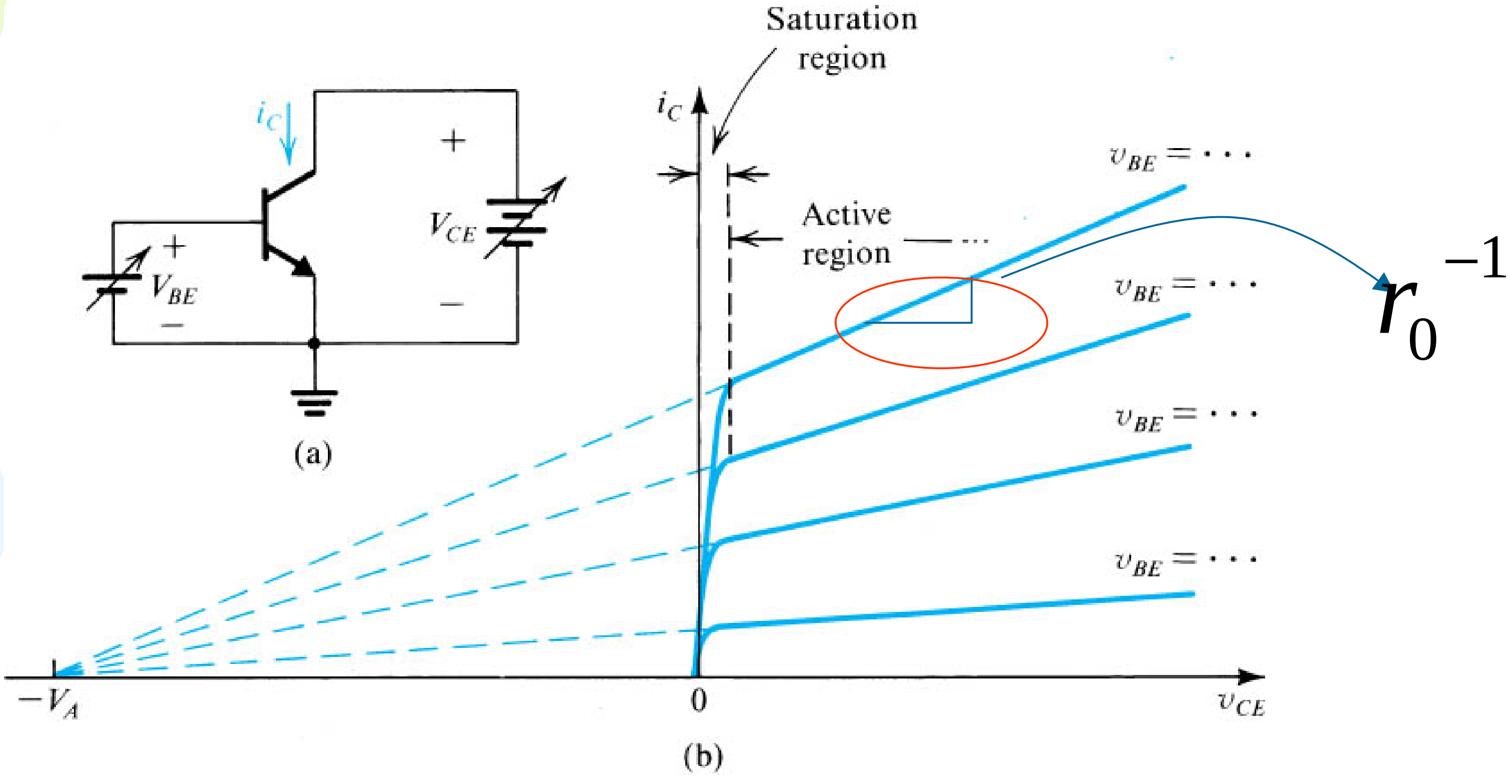


β short circuit common-Emitter current gain

$$\beta_{DC} = \frac{I_{CQ}}{I_{BQ}} \qquad \beta_{ac} = h_{fe} \equiv \left.\frac{\Delta i_C}{\Delta i_B}\right|_{v_{CE}=K}$$

Zero signal component between Emitter and collector (short circuit)

Transistor i_C -- V_{CE} Characteristic (change V_{BE})



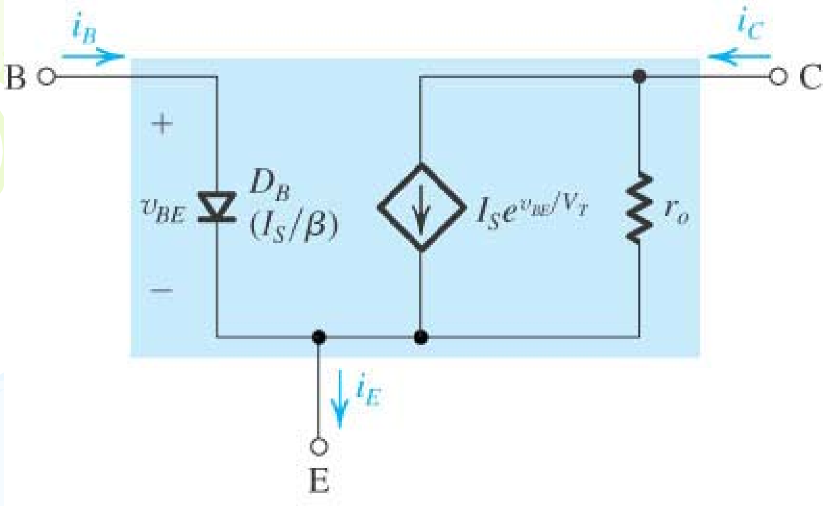
$$Given \quad V_{BE}, \quad if \quad V_{CE}\uparrow \rightarrow V_{CB}\uparrow$$

J_C depletion region ↑ effective base width ↓

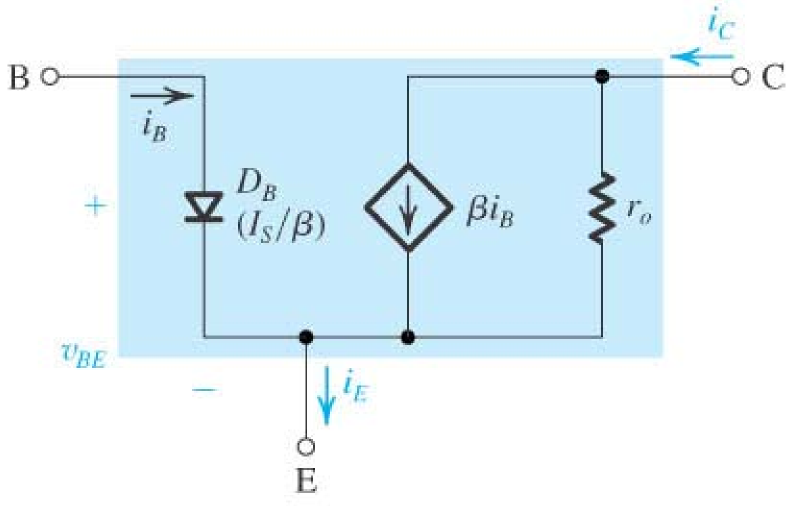
$$I_s = \frac{A_E q n_i^2 D_n}{W N_A} \qquad \Rightarrow I_S \uparrow \therefore i_C \propto I_S \Rightarrow i_C \uparrow$$

Early effect

Large-signal equivalent circuit (Common Emitter in active mode)



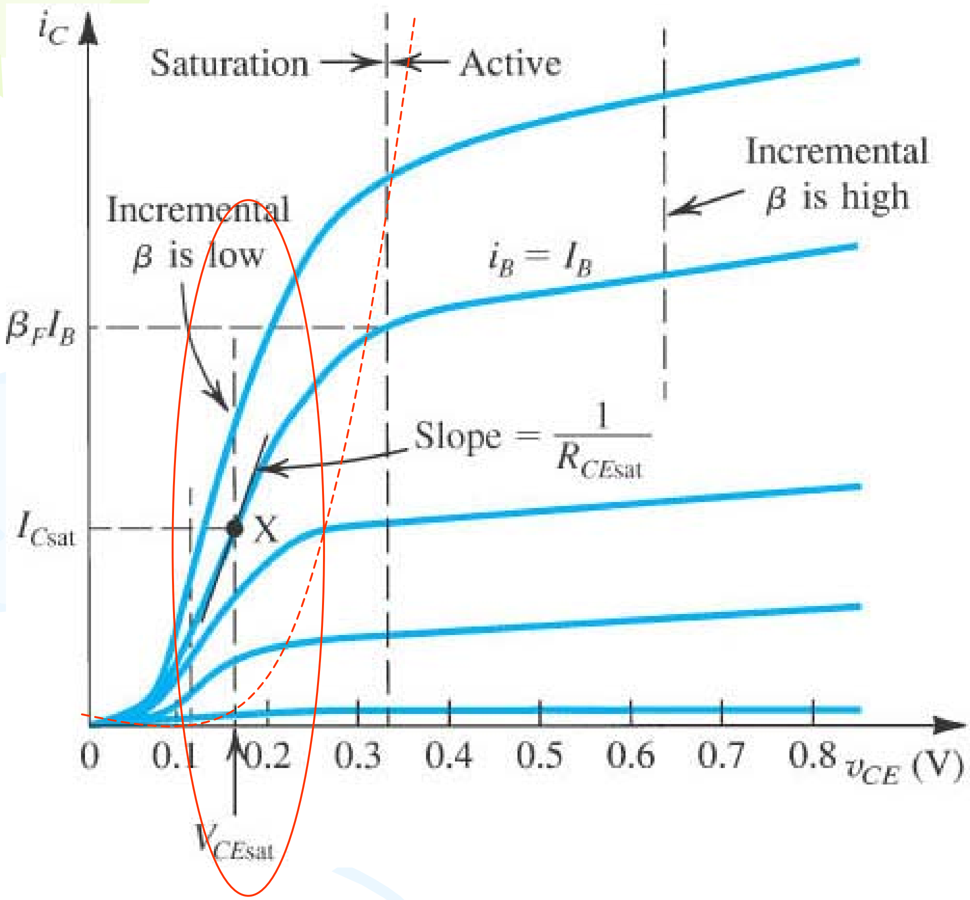
(a)

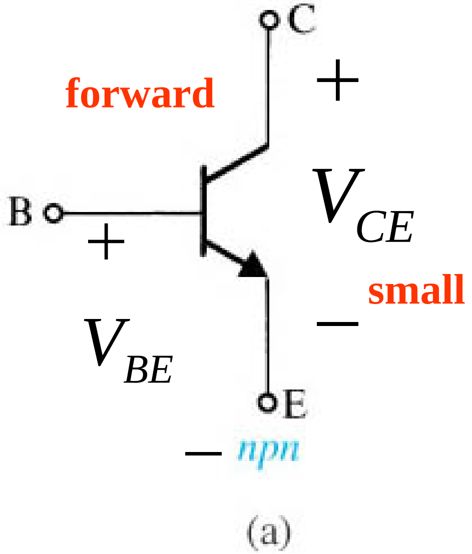


(b)

$$\frac{1}{r_o} = \frac{\partial i_C}{\partial v_{CE}}\bigg|_{V_{BE}=K}$$

Transistor i_C -- V_{CE} Characteristic (CE saturation mode)

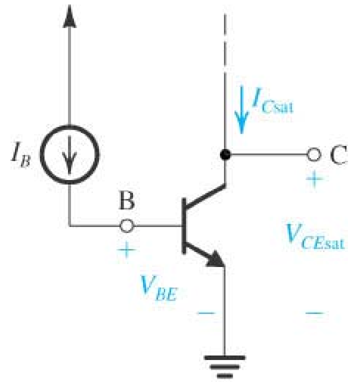




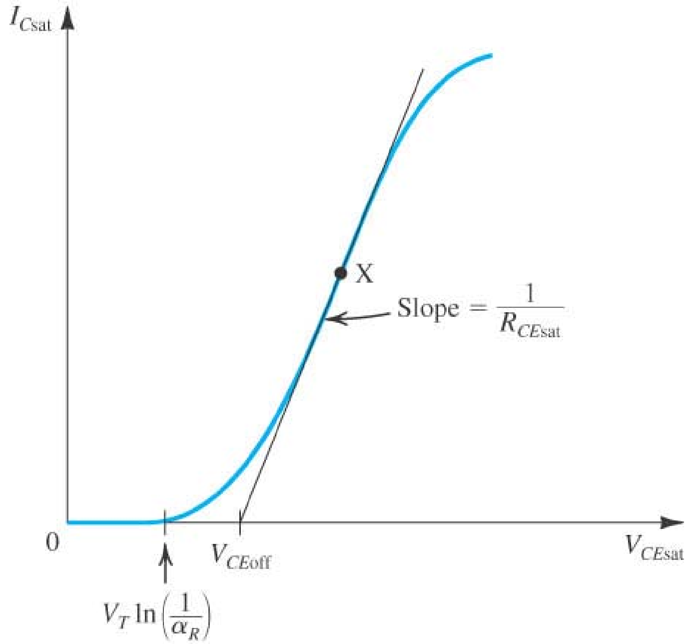
$$i_c \neq \beta i_B$$

$$V_{CE} \approx 0.2V$$

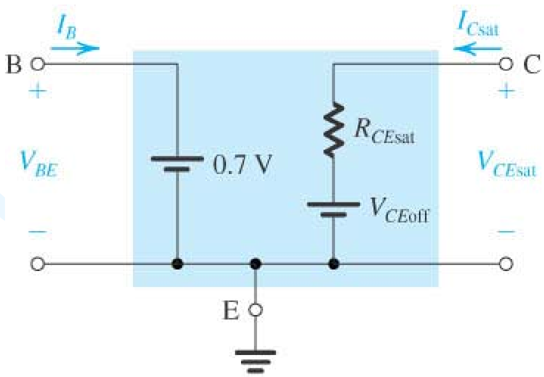
saturation mode equivalent circuit



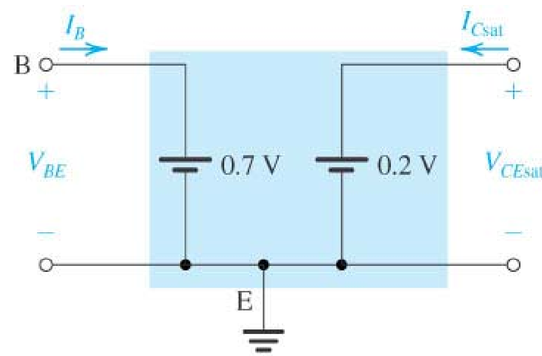
(a)



(b)



(c)

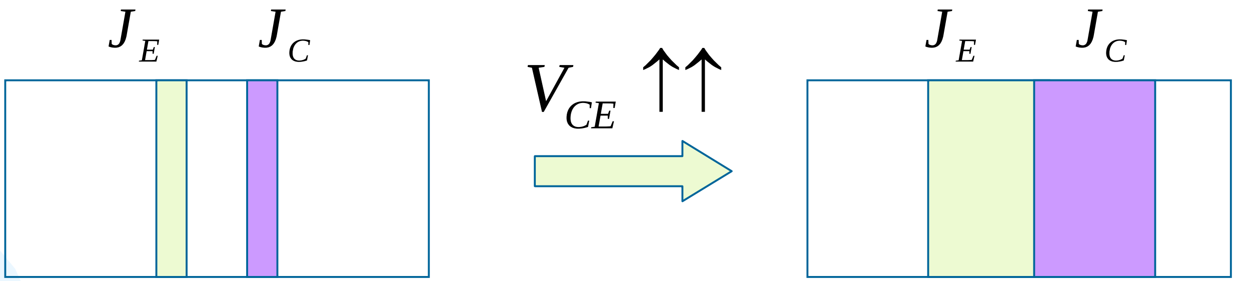


(d)

Transistor breakdown

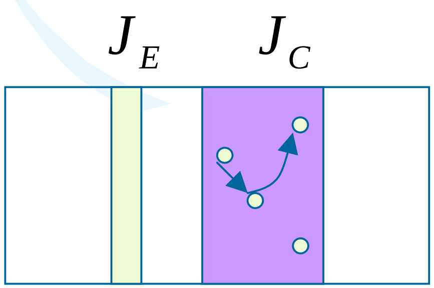
1. **punch-through breakdown**

   $V_{CE} \nearrow \nearrow \rightarrow J_E$ **and** J_C **depletion region** $\nearrow W_B \rightarrow 0$

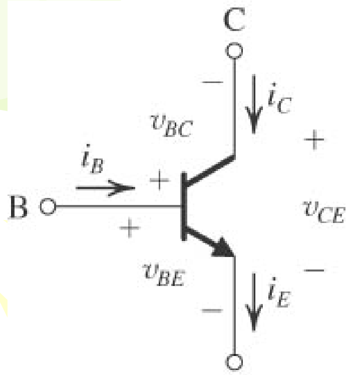


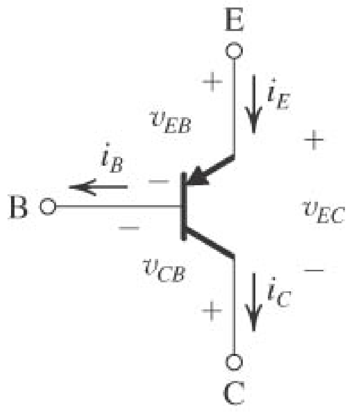
2. **Avalanche breakdown (Impact ionization)**

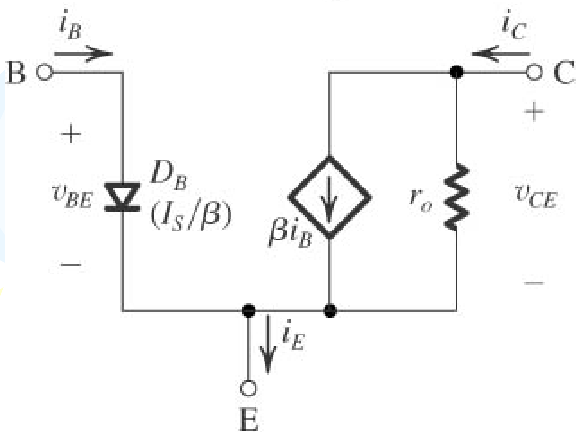
   $V_{CE} \nearrow \nearrow \rightarrow V_{CB} \nearrow$



1. large-scale Equivalent-circuit model







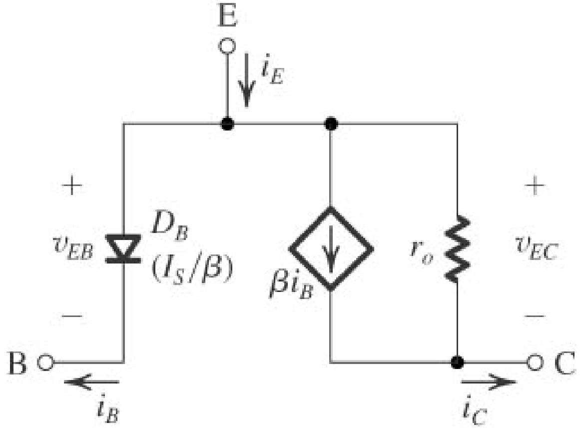
$$V_{BE} = 0.7V$$

$$V_{CE} \geq 0.3V$$

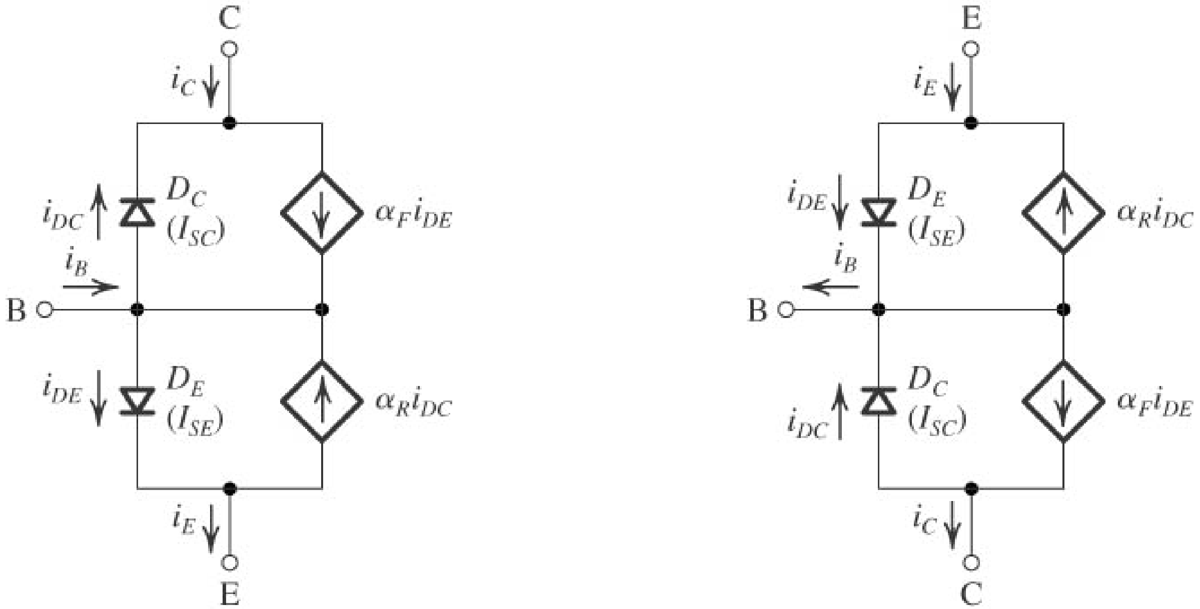
$$V_{BC} < 0.4V$$

$$i_C = \beta i_B$$

$$i_C = \alpha i_E$$



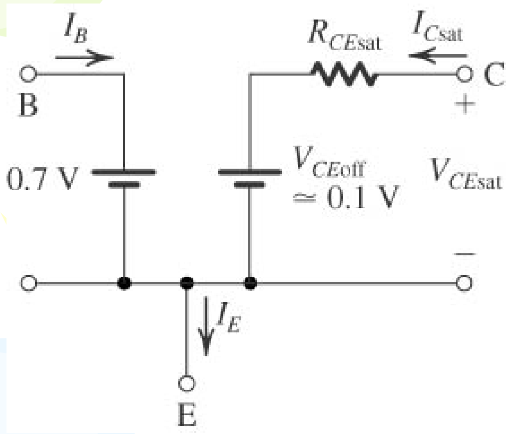
2. Ebers-moll Equivalent-circuit model

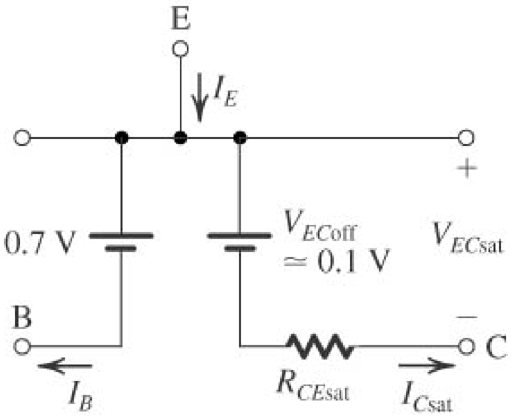


$$i_{DE} = I_{SE}(e^{V_{BE}/V_T} - 1)$$

$$i_{DC} = I_{SC}(e^{V_{BC}/V_T} - 1)$$

1. Saturation Equivalent-circuit model





$$V_{BE} = 0.7 \sim 0.8V$$

$$V_{CE} = 0.1 \sim 0.2V$$

$$V_{BC} = 0.5 \sim 0.6V$$